

Polarized proton-deuteron scattering as a test of time-reversal invariance

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Scattering of protons with transversal polarization p_y^p on deuterons with tensor polarization P_{xz} provides a null-test signal for time-reversal (T) invariance violating but parity (P) conserving effects. We calculate the corresponding null-test observable at beam energies 100–1000 MeV within the spin-dependent Glauber theory considering T-violating P-conserving nucleon-nucleon interactions. The S -wave component of the deuteron wave function as well as the D wave are taken into account and the latter is found to play an important role for the magnitude and the energy dependence of the observable in question. Specifically, with inclusion of the D wave the maximum of the obtained signal is shifted to higher beam energies, i.e., to 700–800 MeV.

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I. INTRODUCTION

The discrete symmetries of parity (P) and time reversal (T) play a crucial role in our understanding of fundamental interactions. For example, P-violation led to the discovery of the V - A structure of the weak interaction of leptons and quarks. CP-violation (or T-violation assuming CPT symmetry, where C stands for charge conjugation) is required to account for the baryon asymmetry of the universe [1]. Since within the standard model the CP-violation observed in physics of kaons and B mesons is by far not sufficient to explain this asymmetry, other sources of CP-violation have to be found. The possibility that T-violation might arise due to physics beyond the standard model has motivated a number of low-energy experiments. These measurements are classified according to whether or not the measured observables violate parity as well as time reversal invariance. Various efforts are undertaken with respect to measurements of the electric dipole moments (EDM) of elementary particles and atoms which are both T-violating and P-violating observables. The other type of observables which are T-violating but P-conserving (TVPC) received considerably less attention. These include tests of the detailed balance [2,3], correlations in the β decay of polarized neutrons [4], charge-symmetry breaking in pn scattering [5], and transmission of polarized neutrons through tensor-polarized nuclei [6]. The reason why TVPC observables are interesting is that the experimental limits on them are still quite weak, in particular much weaker as compared to the EDM. Theoretically, effects of TVPC physics beyond the standard model can be studied in a model-independent way using effective field theory. In this context it was shown that the limits on the EDM imply also severe bounds on TVPC observables [7]. Nonetheless, exceptions to this may occur depending on either unknown details of the generation of the EDM within specific scenarios beyond the standard model [8] or on the possible existence of right-handed neutrinos [9].

In the present paper we consider the scattering of protons with transversal polarization p_y^p on deuterons with tensor polarization P_{xz} . This double-polarized proton-deuteron (pd)

scattering process allows access to a null-test observable for TVPC effects [10]. By definition such observables are nonzero only in the presence of a TVPC interaction and cannot be generated by the T-invariant initial or final state interaction. The observable in question is the total (integrated) cross section for that scattering reaction and it will be called $\tilde{\sigma}$ in the following. An experiment to measure this quantity is planned at the COSY accelerator in Jülich [11], at a projected laboratory energy of 135 MeV. The first theoretical analysis of this observable was performed in Ref. [12] in a calculation of the nonmesonic breakup of the deuteron within the single scattering approximation for some type of TVPC forces. The above energy was found to be the most sensitive one to the TVPC effects. Later on Faddeev calculation were performed for neutron-deuteron (nd) scattering, but at much lower energies namely 100 keV [13]. Recently, in Refs. [14,15] the generalized optical theorem was applied to calculate the cross section $\tilde{\sigma}$ at proton beam energies of $T_p = 100$ –1000 MeV. Here the spin-dependent Glauber theory [16] was used to get the forward elastic pd scattering amplitude. It was shown [14] that the double-scattering mechanism, ignored in [12], dominates the null-test observable $\tilde{\sigma}$. The Coulomb interaction was taken into account and found to lead to no divergence of this observable. As in Ref. [12], lower energies of around 100 MeV were found to be more preferable to search for a TVPC signal [14]. “Null combinations” of some differential spin observables of pd elastic scattering, i.e., quantities which deviate from zero only in case of the presence of TVPC effects, were analyzed in Refs. [17,18].

One approximation made in Ref. [14] is that only the S -wave component of the deuteron wave function was taken into account. Terms which include the D wave, somewhat cumbersome to calculate, were neglected. Therefore, in the present work, now special attention is paid to the role played by the deuteron D wave for this null-test observable. Indeed, the prime reason why the contribution of the D wave was not studied in [14] is the analysis (of elastic pd scattering) in Ref. [16], where it was argued that at energies ~ 100 MeV its contribution is less important than the S -wave

contribution, assuming in particular that at zero transferred three-momentum the contribution of the D wave vanishes. Here we account for the deuteron D wave and we employ the same TVPC interactions again as in [12,14]. We show that the D wave is very important for the absolute value of the null-test signal $\tilde{\sigma}$ and its energy dependence. Preliminary results of the present study were presented at conferences [19,20].

The paper is organized as follows. In Sec. II we outline the employed formalism. Our numerical results are reported in Sec. III. Finally, in Sec. IV a summary and some conclusions are presented.

II. NULL-TEST SIGNAL OF TVPC FORCES

The total cross section of pd scattering for the case of a T-violating P-conserving NN interaction can be written as [14,21]

$$\sigma_{\text{tot}} = \sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{p}^d + \sigma_2 (\mathbf{p}^p \cdot \mathbf{m})(\mathbf{p}^d \cdot \mathbf{m}) + \sigma_3 P_{zz} + \tilde{\sigma} p_y^p P_{xz}, \quad (1)$$

where \mathbf{p}^p (\mathbf{p}^d) is the vector polarization of the initial proton (deuteron) and P_{zz} and P_{xz} are the tensor polarizations of the deuteron. The OZ axis is directed along the proton beam momentum \mathbf{m} , $OY \uparrow \uparrow \mathbf{p}^p$, $OX \uparrow \uparrow [\mathbf{p}^p \times \mathbf{m}]$. In Eq. (1) the terms σ_i with $i = 0, 1, 2, 3$ are nonzero only for T-invariant P-conserving interactions and the last term $\tilde{\sigma}$ constitutes a null-test signal of T-violation with P-conservation. In the notation of Ref. [14] the integrated cross section $\tilde{\sigma}$ is related to the TVPC term \tilde{g} in the forward pd elastic scattering amplitude by

$$\tilde{\sigma} = -4\sqrt{\pi} \frac{2}{3} \text{Im} \tilde{g}. \quad (2)$$

In order to calculate the TVPC amplitude \tilde{g} we use the Glauber theory of multistep scattering. In addition to the regular (T-invariant) NN scattering amplitudes [22] we consider the following terms of the TVPC NN interaction which were under discussion in Refs. [12,14]:

$$\begin{aligned} t_{pN} = & h_N [(\boldsymbol{\sigma} \cdot \mathbf{k})(\boldsymbol{\sigma}_N \cdot \mathbf{q}) + (\boldsymbol{\sigma}_N \cdot \mathbf{k})(\boldsymbol{\sigma} \cdot \mathbf{q}) \\ & - \frac{2}{3}(\boldsymbol{\sigma}_N \cdot \boldsymbol{\sigma})(\mathbf{k} \cdot \mathbf{q})] / m_p^2 \\ & + g_N [\boldsymbol{\sigma} \times \boldsymbol{\sigma}_N] \cdot [\mathbf{q} \times \mathbf{k}] [\boldsymbol{\tau} - \boldsymbol{\tau}_N]_z / m_p^2 \\ & + g'_N (\boldsymbol{\sigma} - \boldsymbol{\sigma}_N) \cdot i [\mathbf{q} \times \mathbf{k}] [\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z / m_p^2. \end{aligned} \quad (3)$$

Here $\boldsymbol{\sigma}$ ($\boldsymbol{\sigma}_N$) is the Pauli matrix acting on the spin state of the proton (nucleon $N = p, n$), $\boldsymbol{\tau}$ ($\boldsymbol{\tau}_N$) is the corresponding matrix acting on the isospin state, and m_p is the proton mass. The transferred and average momenta, \mathbf{q} and \mathbf{k} , are defined in terms of the final (\mathbf{p}') and initial (\mathbf{p}) center-of-mass momenta of the nucleons by $\mathbf{q} = (\mathbf{p} - \mathbf{p}')$ and $\mathbf{k} = (\mathbf{p} + \mathbf{p}')$. In the framework of phenomenological meson-exchange interactions the term g' results from ρ -meson exchange, while the h term comes from the exchange of the axial-vector meson h_1 with quantum numbers $I^G(J^{PC}) = 0^-(1^{+-})$. Up to now, no definite interpretation of g_N in terms of meson exchanges has been given, but its contribution is considered here following Refs. [12,14]. Note, however, that in the present study we take

into account that there is no contribution of the g term to pp scattering because of the Pauli principle [23,24].

As was shown in [14], with the TVPC amplitudes in Eq. (3) only the double-scattering mechanism gives a contribution to the null-test signal, whereas the single-scattering mechanism does not. The double-scattering amplitude is given by the following integral:

$$M^{(d)} = \frac{i}{2\pi^{3/2}} \iint d^2q' M(\mathbf{q}, \mathbf{q}'; \mathbf{S}, \boldsymbol{\sigma}), \quad (4)$$

where $M(\mathbf{q}, \mathbf{q}'; \mathbf{S}, \boldsymbol{\sigma})$ is the Glauber operator of pd scattering. In order to get the TVPC amplitude \tilde{g} one has to calculate the expectation value of this operator for definite initial $|\mu, \lambda\rangle$ and final $|\mu', \lambda'\rangle$ spin states at $\mathbf{q} = \mathbf{0}$:

$$\tilde{g} = \frac{1}{(2\pi)^{3/2}} \int d^2q' \left\langle \mu' = \frac{1}{2}, \lambda' = 0 \left| M(\mathbf{q} = \mathbf{0}, \mathbf{q}'; \mathbf{S}, \boldsymbol{\sigma}) \right| \mu = -\frac{1}{2}, \lambda = 1 \right\rangle, \quad (5)$$

where $\mu(\mu')$ and $\lambda(\lambda')$ are the spin projections of the initial (final) proton and the deuteron on the quantization axis.

As found in [14], the g' term in Eq. (3) gives zero contribution to the amplitude \tilde{g} , for both the S and D waves of the deuteron. Some qualitative arguments for this result are discussed in Ref. [20]. For the h and g terms of the TVPC pN interaction one has from Eq. (29) of Ref. [14]:

$$\begin{aligned} M(\mathbf{q}, \mathbf{Q}; \mathbf{S}, \boldsymbol{\sigma}) = & W_{ij} \{S_i, S_j\} S_0^{(0)} - \sqrt{2} W_{ij} [\{S_i, S_j\} S_{12}(\hat{\mathbf{Q}}; \mathbf{S}, \mathbf{S}) \\ & + S_{12}(\hat{\mathbf{Q}}; \mathbf{S}, \mathbf{S}) \{S_i, S_j\}] S_2^{(1)} \\ & + \frac{1}{16\pi} W_{ij} \int d^3r \frac{1}{r^2} e^{i\mathbf{Q}\mathbf{r}} w^2 S_{12}(\hat{\mathbf{r}}; \boldsymbol{\sigma}_n, \boldsymbol{\sigma}_p) \\ & \times \{S_i, S_j\} S_{12}(\hat{\mathbf{r}}; \boldsymbol{\sigma}_n, \boldsymbol{\sigma}_p). \end{aligned} \quad (6)$$

Here,

$$S_{12}(\hat{\mathbf{r}}; \boldsymbol{\sigma}_p, \boldsymbol{\sigma}_n) = 3(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_n \cdot \hat{\mathbf{r}}) - \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_n \quad (7)$$

is the tensor operator, $\boldsymbol{\sigma}_n(\boldsymbol{\sigma}_p)$ are the Pauli matrices acting on the spin states of the neutron and proton in the deuteron, and $\hat{\mathbf{r}}$ is the unit vector directed along the radius-vector \mathbf{r} . We use the notations $\{S_i, S_j\} = S_i S_j + S_j S_i$, where $\mathbf{S} = (\boldsymbol{\sigma}_n + \boldsymbol{\sigma}_p)/2$. The tensor operator $S_{12}(\hat{\mathbf{Q}}; \mathbf{S}, \mathbf{S})$ is defined analogous to Eq. (7).

The deuteron form factors appearing in Eq. (6) are related to the S - and D -wave components of the deuteron wave function, u and w [16]:

$$\begin{aligned} S_0^{(0)}(q) &= \int_0^\infty dr u^2(r) j_0(qr), \\ S_0^{(2)}(q) &= \int_0^\infty dr w^2(r) j_0(qr), \\ S_2^{(1)}(q) &= 2 \int_0^\infty dr u(r) w(r) j_2(qr), \\ S_2^{(2)}(q) &= -\frac{1}{\sqrt{2}} \int_0^\infty dr w^2(r) j_2(qr), \\ S_1^{(2)}(q) &= \int_0^\infty dr w^2(r) j_1(qr)/(qr). \end{aligned} \quad (8)$$

In Eq. (6) the summation has to be done over recurring indices $i, j = x, y, z$. To perform the integration over the directions of the vector \mathbf{r} in Eq. (6), we use the following relation [25]:

$$\iint d\Omega_{\mathbf{r}} \exp(-i\mathbf{Q}\mathbf{r}) T_l(\hat{\mathbf{r}}) = 4\pi j_l(Qr) (-i)^l T_l(\hat{\mathbf{Q}}), \quad (9)$$

where $j_l(x)$ is the spherical Bessel function, $T_2(\hat{\mathbf{n}}) = (\sigma_p \cdot \hat{\mathbf{n}})(\sigma_n \cdot \hat{\mathbf{n}}) - \frac{1}{3}(\sigma_p \cdot \sigma_n)$, $T_0(\hat{\mathbf{n}}) = \sigma_p \cdot \sigma_n$; $\hat{\mathbf{n}}$, $\hat{\mathbf{Q}}$, and $\hat{\mathbf{r}}$ are unit vectors along \mathbf{n} , \mathbf{Q} , and \mathbf{r} , respectively.

The tensor operator $W_{ij}(\sigma)$ in Eq. (6) acts only on the spin state of the beam proton and does not depend on the spins and coordinates \mathbf{r} of the target nucleons. The explicit expressions for W_{ij} are given in Ref. [14] for the h and g terms. These operators contain products of one TVPC amplitude (g_N or h_N) with the (T-invariant) NN amplitude C'_N [16], namely $C'_N h_p$ and $C'_p h_n$ for the h term, and $C'_p g_n$ for the g term. The other hadronic amplitudes A_N, C_N, B_N, G_N, H_N in the notation of [16] do not contribute to the amplitude \tilde{g} with regard to the h and g terms.

As already mentioned, the g' term does not contribute to the null-test observable $\tilde{\sigma}$ within the Glauber theory of pd elastic scattering [14,20]. Considering the h and g terms for the double-scattering mechanism and taking into account both the S and D wave of the deuteron we find the following result for the forward TVPC amplitude:

$$\begin{aligned} \tilde{g} = & \frac{i}{4\pi m_p} \int_0^\infty dq q^2 \left[S_0^{(0)}(q) - \sqrt{8} S_2^{(1)}(q) - 4 S_0^{(2)}(q) \right. \\ & \left. + \sqrt{2} \frac{4}{3} S_2^{(2)}(q) + 9 S_1^{(2)}(q) \right] [-C'_n(q) h_p + C'_p(q)(g_n - h_n)], \end{aligned} \quad (10)$$

where $S_i^{(j)}$ are the elastic form factors of the deuteron defined in Eq. (8). [Note, however, that one of the form factor, $S_1^{(2)}(q)$, is absent in the electromagnetic structure of the deuteron.] In the calculation presented in Ref. [14] only the first term in the (big) square brackets in Eq. (10), $S_0^{(0)}(q)$, was taken into account. This corresponds to the S -wave approximation. The second term, $S_2^{(1)}(q)$, results from the interference of the S - and D -state wave functions while the last three terms contain pure D -wave contributions. One can see from Eq. (10) that \tilde{g} contains only products of the T-invariant NN amplitude and the TVPC NN amplitude. This means that any T-invariant P-conserving background is excluded from the null-test observable $\tilde{\sigma}$. Accordingly, small remaining uncertainties in the regular NN scattering amplitudes cannot affect the final result for $\tilde{\sigma}$ significantly.

III. RESULTS

In our numerical calculations we employ the pN scattering amplitude C'_N evaluated from the SAID partial wave analysis [22]. The deuteron wave function is taken from the CD Bonn NN model [26]. The amplitude h_N is generated from the exchange of the axial-vector meson $h_1(1170)$. For explicit expressions of the potential and the resulting amplitude see

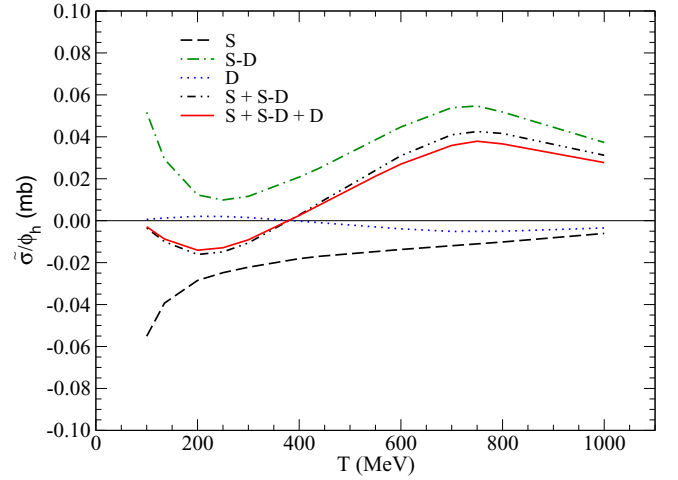


FIG. 1. Dependence of the TVPC signal $\tilde{\sigma}$ on the proton beam energy T for the h term, in units of the unknown ratio (ϕ_h) of the TVPC and the strong $h_1 NN$ coupling constants. Results are presented for the different contributions due to the S - and D -wave components of the deuteron wave function (CD Bonn), according to the terms in Eq. (10). S -wave (dashed line), S - D interference (dash-dotted line), D -wave (dotted line), S -wave + S - D interference (dash-double dotted line), total result (solid line).

Eqs. (23)–(24) in Ref. [14]. The results of the calculation of the observable $\tilde{\sigma}$ based on the h term are presented in Fig. 1, in units of the unknown ratio $\phi_h = \tilde{G}_h/G_h$, where \tilde{G}_h is the TVPC coupling constant and G_h the strong coupling constant of the h_1 meson with the nucleon. We employ the very same amplitude as in Ref. [14] so that our present result in the S -wave approximation coincides with the one given in that reference. (Note, however, that in Fig. 3 of [14] $|\tilde{\sigma}/\phi_h|$ is shown.)

From Fig. 1 one can see that the D -wave component of the deuteron, taken into account in the present study, has a strong impact. It changes the result for the observable $\tilde{\sigma}$ considerably as compared to the S -wave calculation published previously [14]. It turns out that the S - D interference [second term in Eq. (10)] is destructive with respect to the pure S -wave contribution. As a consequence, it drastically reduces the null-test signal ($\tilde{\sigma}$) at energies ~ 100 MeV as compared to the pure S -wave contribution, i.e., in the region of the planned COSY experiment [11]. At the same time the interference term provides an enhancement of the signal at 700–800 MeV. The effect of the pure D wave [last three terms in Eq. (10)], on the other hand, is indeed negligible, in agreement with what was assumed in Ref. [14]. Since the energy dependence of $\tilde{\sigma}$ turned out to be rather sensitive to the D -wave component we performed calculations with another deuteron wave function, namely the one of the Paris NN potential [28]. Corresponding results are presented in Fig. 2. Obviously, there are variations on the quantitative level but qualitatively the resulting energy dependence of $\tilde{\sigma}$ is similar.

As said above, no definite interpretation of the g term in terms of meson exchanges has been given in the literature (see, however, the pertinent remarks in Ref. [27]). Based on the expectation that it originates from very short-ranged

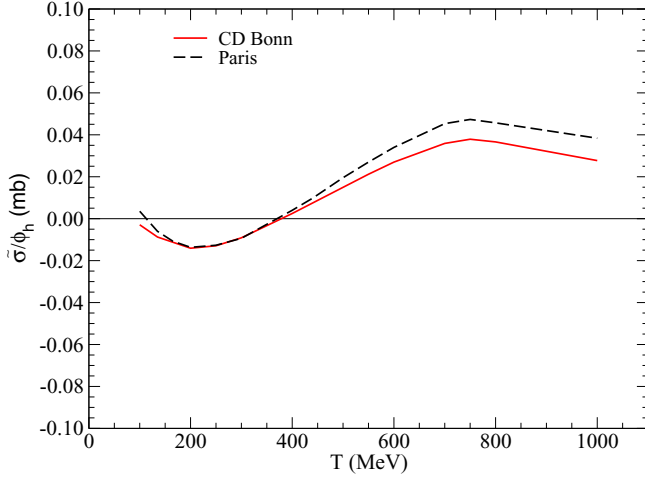


FIG. 2. Dependence of the TVPC signal $\tilde{\sigma}$ on the proton beam energy T for the h term, in units of the unknown ratio (ϕ_h) of the TVPC and the strong $h_1 NN$ coupling constants. Total result based on the CD Bonn (solid) and Paris (dashed) deuteron wave functions are presented.

dynamics the corresponding amplitude was assumed to be constant in Refs. [12,14]. Then the energy dependence of $\tilde{\sigma}$ is solely determined by that of the T-invariant NN amplitude C'_p , see Eq. (10). Since h_1 exchange is also fairly short-ranged it leads to a TVPC amplitude that is likewise practically constant [14]. On the other hand, the h_1 is an isoscalar meson and, accordingly, the amplitude \tilde{g} results from the sum of C'_p and C'_n . Despite of that the g and h terms yield a fairly similar energy dependence of $\tilde{\sigma}$, as can be seen by comparing the results in Figs. 1 and 3. (In order to facilitate the comparison we scaled the results based on the g term by a factor ϕ_g so that at the maximum the total results are roughly the same.) Note

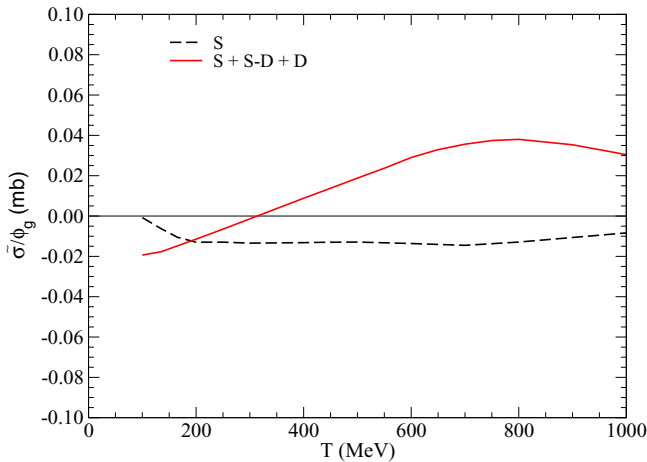


FIG. 3. Dependence of the TVPC signal $\tilde{\sigma}$ on the proton beam energy T for the g term. Results based on the S -wave component of the (CD Bonn) deuteron wave function (dashed line) and the full results (solid line) are presented. For the definition of the scaling factor ϕ_g , see text.

that for h -type contributions a variety of isospin structures is possible [23,27] so that, in principle, any combination of C'_p and C'_n in Eq. (10) can occur.

IV. CONCLUSIONS

The generalized optical theorem was used in Ref. [14] for a calculation of $\tilde{\sigma}$, the null-test signal for time-reversal violating parity-conserving effects in proton-deuteron scattering. In this case only the evaluation of the forward elastic pd scattering amplitude is required. It was found within the Glauber theory that the single-scattering mechanism leads automatically to the result *zero* for $\tilde{\sigma}$. Incidentally, it was exactly this mechanism that was used in the first theoretical analysis of the null-test observable $\tilde{\sigma}$ performed in Ref. [12] via a straightforward calculation of inelastic and elastic pd scattering. The double-scattering mechanism, based on the h and g terms of the TVPC NN amplitude, yields several contributions to the TVPC amplitude of pd scattering, but it turned out that it is only one hadronic (T-invariant) pN amplitude, namely C'_N , that modulates the TVPC observable $\tilde{\sigma}$ [14].

In the present study we extended our previous investigation [14] by taking into account the D -wave component of the deuteron. We showed for the case of the h - and g -type interactions that the deuteron D wave has a strong impact on the null-test signal, due to contributions that arise from the interference between the deuteron S - and D -state wave functions. The effect of the D -wave component alone turned out to be negligible. Evidently, with the D wave included, a zero crossing of $\tilde{\sigma}$ is possible even when the TVPC interaction itself is nonzero. In the present calculation this occurs at lower energies, i.e., below $T = 400$ MeV. Thus, it is advisable to perform experiments at two or possibly more energies in order to achieve conclusive results. In any case, our predictions suggest that energies around 700–800 MeV could be most promising for finding a signal. Though there is also some sensitivity to variations in the D -wave component the overall modification is not too dramatic.

The g' term caused by the ρ -meson exchange in the TVPC NN interaction does not contribute to $\tilde{\sigma}$ within the Glauber theory with T-invariant P-conserving NN interactions in the deuteron [14]. One-pion exchange is excluded from the TVPC NN interaction from the beginning [5]. There are several other TVPC terms in the NN interaction [23] we ignored here, but which one could examine in the future. It should be said, however, that most of those vanish on-shell and, therefore, are presumably suppressed. Indeed, a recent study of the P-violating NN interaction within chiral effective field theory, where terms that contribute only off-shell arise as well [29], found such contributions to be negligible, at least for the energies considered. In any case, off-shell terms do not contribute in the Glauber theory of pd elastic scattering.

The remaining terms listed in Ref. [23] are all of h -type spin-momentum structure and differ only in their isospin dependence. For example, on the meson-exchange level contributions of isovector nature result from the sometimes considered axial-vector meson $a_1(1260)$ [12,27]. But since the spin-momentum structure is the same, any such additional TVPC NN interactions can lead only to a modification of

Eq. (10) with regard to the relative weight of the C'_p and C'_n amplitudes, but there is no change in the combination of the deuteron form factors.

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- [1] A. D. Sakharov, Pis'ma v Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [JETP Lett. **5**, 24 (1967)]; Usp. Fiz. Nauk **161**, 61 (1991) [Sov. Phys. Usp. **34**, 392 (1991)].
 - [2] E. Blanke, H. Driller, W. Glöckle, H. Genz, A. Richter, and G. Schrieder, Phys. Rev. Lett. **51**, 355 (1983).
 - [3] J. B. French, V. K. B. Kota, A. Pandey, and S. Tomsovic, Phys. Rev. Lett. **54**, 2313 (1985).
 - [4] H. P. Mumm, T. E. Chupp, R. L. Cooper, K. P. Coulter, S. J. Freedman, B. K. Fujikawa, A. Garcia, G. L. Jones, J. S. Nico, A. K. Thompson, C. A. Trull, J. F. Wilkerson, and F. E. Wietfeldt, Phys. Rev. Lett. **107**, 102301 (2011).
 - [5] M. Simonius, Phys. Rev. Lett. **78**, 4161 (1997).
 - [6] P. R. Huffman, N. R. Roberson, W. S. Wilburn, C. R. Gould, D. G. Haase, C. D. Keith, B. W. Raichle, M. L. Seely, and J. R. Walston, Phys. Rev. C **55**, 2684 (1997).
 - [7] R. S. Conti and I. B. Khriplovich, Phys. Rev. Lett. **68**, 3262 (1992).
 - [8] A. Kurylov, G. C. McLaughlin, and M. J. Ramsey-Musolf, Phys. Rev. D **63**, 076007 (2001).
 - [9] B. K. El-Menoufi, M. J. Ramsey-Musolf, and C.-Y. Seng, arXiv:1605.09060 [hep-ph].
 - [10] H. E. Conzett, Phys. Rev. C **48**, 423 (1993).
 - [11] P. D. Eversheim, B. Lorentz, and Yu. Valdau, Test of Time reversal invariance in proton-deuteron scattering at COSY, COSY Proposal No. 215 (2012), http://apps.fz-juelich.de/pax/paxwiki/images/8/8c/215-TRI_Prop_sum.pdf
 - [12] M. Beyer, Nucl. Phys. A **560**, 895 (1983).
 - [13] Y.-H. Song, R. Lazauskas, and V. Gudkov, Phys. Rev. C **84**, 025501 (2011); **93**, 049901(E) (2016).
 - [14] Yu. N. Uzikov and A. A. Temerbayev, Phys. Rev. C **92**, 014002 (2015).
 - [15] A. A. Temerbayev and Yu. N. Uzikov, Yad. Fiz. **78**, 38 (2015) [Phys. Atom. Nuclei **78**, 35 (2015)].
 - [16] M. N. Platonova and V. I. Kukulín, Phys. Rev. C **81**, 014004 (2010).
 - [17] A. A. Temerbayev and Yu. N. Uzikov, Izv. Ross. Akad. Nauk, Ser. Fiz. **79**, 535 (2015) [Bull. Russ. Acad. Sci. Phys. **79**, 493 (2015)].
 - [18] A. A. Temerbayev and Yu. N. Uzikov, Izv. Ross. Akad. Nauk, Ser. Fiz. **80**, 271 (2016) [Bull. Russ. Acad. Sci. Phys. **80**, 242 (2016)].
 - [19] Yu. N. Uzikov, J. Phys.: Conf. Ser. **678**, 012020 (2016).
 - [20] Yu. N. Uzikov, Eur. Phys. J. Web Conf. **113**, 04027 (2016).
 - [21] Yu. N. Uzikov and A. A. Temerbayev, Int. J. Mod. Phys. Conf. Ser. **40**, 1660080 (2016).
 - [22] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **76**, 025209 (2007); <http://gwdac.phys.gwu.edu>
 - [23] P. Herczeg, Nucl. Phys. **75**, 655 (1966).
 - [24] J. Bystricky, F. Lehar, and P. Winteritz, J. Phys. **45**, 207 (1984).
 - [25] G. Fäldt and C. Wilkin, Nucl. Phys. A **587**, 769 (1995).
 - [26] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).
 - [27] M. Simonius, Phys. Lett. B **58**, 147 (1975).
 - [28] M. Lacombe, B. Loiseau, R. Vinh Mau, J. Côté, P. Pirès, and R. de Tourreil, Phys. Lett. B **101**, 139 (1981).
 - [29] J. de Vries, N. Li, U.-G. Meißner, N. Kaiser, X.-H. Liu, and S.-L. Zhu, Eur. Phys. J. A **50**, 108 (2014).